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Compact Ultra-Wideband Monopole Antennas Using Novel Liquid Loading Materials

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AQ:2 **ABSTRACT** An ionic liquid (IL) is used to make antennas for the first time. Unlike water, the proposed material has a large liquid range (−69.8 °C–350 °C), a relative permittivity of $\approx$3, an extremely low dielectric loss, and very stable thermophysical material properties. It can be used for liquid dielectric resonator antennas (DRAs) or as a loading material for performance enhancement. Importantly, the proposed liquid loading scheme is relatively simple and of low cost, but it can markedly improve the antenna performance. As design examples, a liquid-loaded wideband linearly polarized (LP) monopole antenna with an omnidirectional radiation pattern is first presented. Then, the LP antenna is modified to a wideband circularly polarized (CP) antenna with boresight radiation. These antenna examples demonstrate a frequency coverage of 1.25–5 GHz, a wide CP bandwidth, a relatively high gain (>4 dBi), high radiation efficiency >85%, and an electrical size of $0.42\,\lambda_0 \times 0.42\lambda_0 \times 0.17\lambda_0$. The experimental results show that the liquid loading works well under a wide range of temperatures. It effectively reduces the antenna electrical size by 40% and improves the impedance matching by 5 dB. Therefore, the proposed liquid loading scheme can be applied to a variety of antenna/RF designs.

INDEX TERMS Circular polarization (CP), dielectric loading, dielectric resonator antenna (DRA), monopole antennas, ionic liquid (IL).

I. INTRODUCTION

Dielectric materials can either be used as radiating materials in the dielectric resonator antennas (DRAs) [1]–[7], or as loading materials for antenna miniaturization and performance enhancement [8]–[11]. Conventional dielectric materials for antennas/RF engineering are mostly solid dielectrics with a relatively low loss (e.g., ceramic and glass). However, due to high fabrication complexity, such solid dielectric materials typically cannot accommodate special feeding structures when the metal is inserted to the DR. In addition, solid dielectrics may not perfectly form contact with the feed metal, resulting in the air-gap effect which negatively affects the antenna performance [12].

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Compact and wideband antennas are in high demand due to the rapid development of ultra-wideband (UWB) high data-rate communications, radar technologies, wireless communications and sensing systems [13]. It has been demonstrated that the electrical size of the antenna can be significantly reduced by loading high permittivity dielectric materials (e.g., relative permittivity > 20) [14], [15]. However, it is also noted that such high permittivity antenna loadings could substantially decrease the impedance bandwidth due to the high quality factor (Q-factor) of the system [16]. For wideband antennas, it is preferable to use loading dielectrics with a relatively low permittivity (e.g., 3 – 4) [17], [18]; but the size reduction of such antennas by using the conventional solid dielectric materials of low permittivity is typically very limited. Consequently, it is very challenging to reduce the size of wideband antennas without affecting their impedance bandwidths.

Apart from the aforementioned solid materials, liquid dielectrics such as distilled water have recently been considered for making DRAs and loading materials. It was found that the dielectric loss of water is a function of frequency [19]–[21]. Consequently, the radiation efficiency of water-based antennas is relatively low (e.g., $< 40\%$) at higher frequency bands (e.g., > 1 GHz). In addition, water typically has temperature-dependent performance and phase changes such as turning to ice if the temperature goes below 0 °C. These drawbacks restrict these water-based antennas in real-world applications. Additionally, dielectric organic solvents (e.g., ethyl acetate) have been selected to replace water, due to their much smaller loss tangent, stable dielectric relaxation and lower freezing point [22], [23]. However, such solvent-based liquid antennas have other problems. For example, most organic solvents are flammable, often toxic and have high vapor pressures, resulting in high evaporation rates which raise potential safety concerns.

To address these aforementioned challenges, here we propose a new liquid loading material with advanced material properties, aiming at reducing the electrical size of the antenna. The material properties of the liquid in terms of the dielectric spectroscopy have been fully characterized over a relatively wide temperature range as well as a wide frequency range. Different from traditional solid materials, the liquid load can easily accommodate complex feeding structures without an air gap. As design examples, we propose a few narrowband and wideband monopole antennas with different polarizations and radiation modes. Having loaded the liquid material on these antennas, the electrical size can be reduced by 40% while the impedance matching of the antenna over a very wide band can be improved. Most importantly, these liquid-loaded antennas work well under a wide temperature range with good performance. It is shown that the proposed liquid loading scheme is suitable for different types of antennas with practical applications.

The rest of this paper is organized as follows. Section II firstly presents the details of the liquid material. Then, the concept of liquid-loaded monopole antennas is discussed. A liquid-loaded wideband CP antenna design is introduced in Section III. The antenna prototype fabrication and experimental validations are shown in Section IV. Results discussions and performance comparisons are given in Section V. Finally, conclusions are drawn in Section VI.

II. LIQUID-LOADED MONOPOLE ANTENNAS

A. LOW-LOSS IONIC LIQUIDS

Ionic liquids (ILs) are a relatively new class of liquid materials that have attracted a significant attention over the past 20 years. Room temperature ionic liquids (RTILs) usually consist of bulky asymmetric cations, with imidazolium cations being the most commercially available and most widely studied. Such ILs usually have excellent material properties, e.g., high thermal stability, extremely low vapor pressure, tunable electric conductivity, large electrochemical window, high heat capacity and non-flammability. Therefore, they have been adopted to many important applications, such as heat-storage, liquid crystals, electrolytes, solvents, lubricants and additives [24]. However, these ILs have never been used in the community of antennas and RF engineering.

Herein, we employ a low-loss IL as a new type of functional material for antenna designs. Compared with water, oil and most common stable thermophysical properties. Therefore, the IL-based antennas are expected to work well in different practical scenarios.

Our original objective was to exploit a liquid material of low relative permittivity (e.g., < 4) and low-loss for antenna dielectric loading. As an example, herein we propose to use the IL trihexyltetradecylphosphonium chloride (TPC), formula: $[P(nC_6H_{13})_3(nC_{14}H_{29})][Cl]$, which retains its liquid state to the low temperature of -69.8 °C and exhibits no decomposition below 350 °C [28]. Importantly, the electrical conductivity of this liquid is around 0.00025 S/m, resulting in an extremely small loss tangent (LT) of < 0.001. Moreover, the TPC is a colorless liquid with a relatively low density of 0.895 g/mL at room temperature.

The broadband dielectric spectroscopy of the TPC was measured by using a Keysight dielectric slim probe [25]. The experimental setup of the dielectric probe platform is given in Fig. 1 (a). The measured relative permittivity and LT of the TPC at room temperature are given in Fig. 1 (b) over the frequency band of 0.1 – 6 GHz. As can be seen from the figure, the relative permittivity (dielectric constant) of the TPC is around 2.9 – 3.2 over the wide band while the LT is relatively small, ranging from 0.0001 to 0.03 across the band. In addition, water freezes below 0 °C, and most typical solvents (e.g., acetone) readily evaporate even at room temperature, higher temperatures in a sealed system can also result in an increase in pressure leading to further safety issues. Therefore, the proposed IL was measured at different temperatures ranging from -20 to 60 °C. A laboratory temperature control platform was employed to maintain/adjust the temperature of the measured liquid. From Fig. 1 (c), it can be seen that the material property of the liquid is relatively stable over such a wide temperature range, where the relative permittivity varies between 3 and 3.5 and the LT is less than 0.04 in all cases. This shows that the proposed IL is a suitable material for making dielectric antennas or dielectric loading materials due to its wide liquid range, low loss and stable dielectric relaxation.

B. LIQUID LOADING FOR ANTENNA PERFORMANCE ENANCEMENT

1) SINGLE-BAND MONOPOLE ANTENNAS

As a preliminary design example, a standard metal probe monopole antenna being loaded with the proposed IL is depicted in Fig. 2. The detailed dimensions of this antenna are provided in the caption of Fig. 2. The liquid is held within a Perspex acrylic cylinder which possesses a relative permittivity of 2.5 and a thickness of 1.5 mm. The antenna was modeled and simulated using CST Microwave Studio.

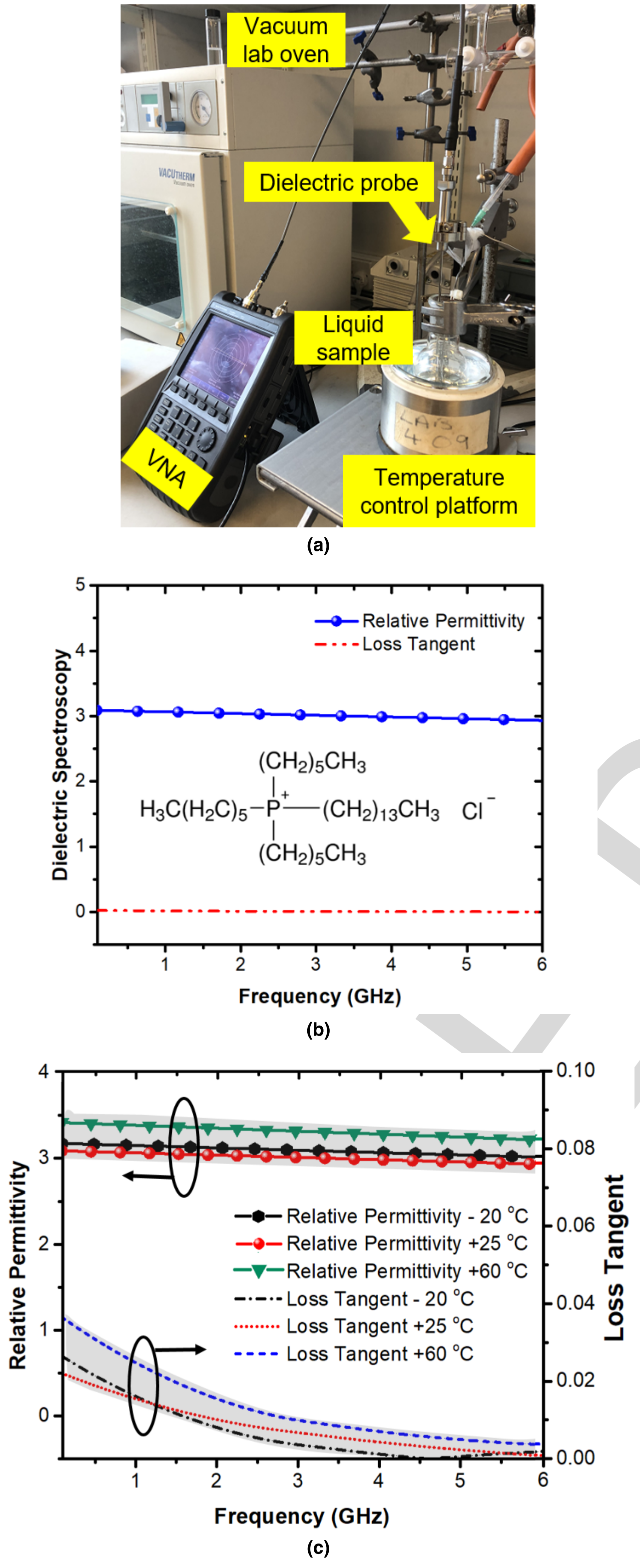

FIGURE 1. (a) Experiment setup for the liquid measurement. the Keysight dielectric probe kits are employed for the measurement. (b) Measured broadband dielectric spectroscopy of the proposed organic ionic liquid (trihexyl(tetradecyl) phosphonium chloride) at room temperature (25 °C). (c) Measured relative permittivity and loss tangent of the ionic liquid at different temperatures ranging from −20 °C to 60 °C.

Fig. 3 shows the simulated reflection coefficients of the proposed metal probe monopole antennas with/without using the

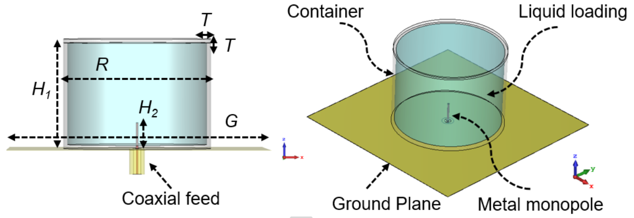

FIGURE 2. A metal probe monopole antenna is loaded by using the proposed liquid. The dimensions of the antenna are: H_1 (height of the liquid container) = 40 mm, G (length and width of the ground plane) = 100 mm, H_2 (height of the monopole) = 10 mm, R (diameter of the container) = 57 mm, and T (thickness of the container) = 1.5 mm. The overall dimension of the antenna is 100 × 100 × 41 mm^3.

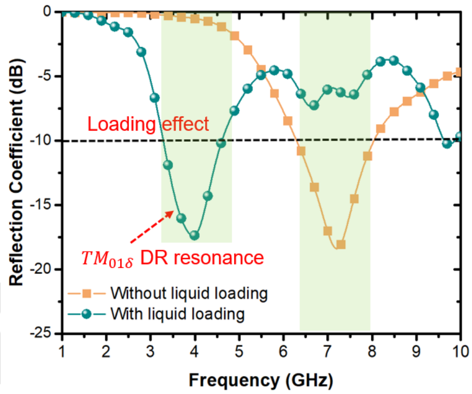

FIGURE 3. Simulated reflection coefficient of the proposed metal probe monopole antennas with and without using the liquid loading.

liquid loading. It can be seen that the fundamental resonance of the metal monopole antenna (without liquid) is located at 7 GHz. Since the length of the probe is around 10 mm, the corresponding electrical size is around 1/4 at 7 GHz which is reasonable. Once the liquid is loaded, the first resonance is shifted from 7 GHz to 4 GHz. This is mainly due to the dielectric loading effect of the liquid, and partially due to the resonant mode of the liquid DRA. The probe acts as a feed for the cylinder DR. In this case, the resonant mode of the cylinder DR using the center-fed probe is realized [26]. The resonant frequency of such a cylinder-shaped DR (with a radius of 25 mm, a height of 40 mm and relative permittivity of around 3.2) can be calculated using the DRA formulas in accordance with [26]. After calculation, the resonant frequency of the liquid DR is about 3.3 GHz.

Additionally, the frequency bandwidths of the antenna (for reflection coefficient < -10 dB) are about 6.5 - 8 GHz and 3.2 - 5 GHz for the case of with/without using the liquid respectively. The corresponding fractional bandwidths (FBWs) are about 20.7% (6.5 - 8 GHz) and 44% (3.2 - 5 GHz). This shows that the proposed low permittivity liquid loading can effectively reduce the electrical size ((1-4/7) × 100% = 43% reduction) of the antenna with improved frequency bandwidth.

2) ULTRA WIDEBAND MONOPOLE ANTENNAS

To further investigate the liquid loading effect, we propose an alternative monopole antenna with a relatively wide frequency bandwidth. As shown in Fig. 4, the single metal probe

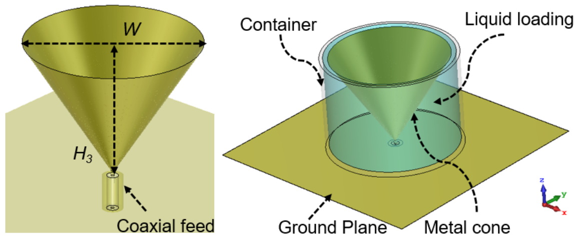

FIGURE 4. A metal cone-shaped monopole antenna is loaded by using the proposed liquid. the dimensions of the metal cone are: H_3 (height of the cone) = 39.6 mm, G (length and width of the ground plane) = 100 mm, and W (diameter of the cone) = 49 mm. The overall dimension of the antenna is still 100 × 100 × 41 mm^3.

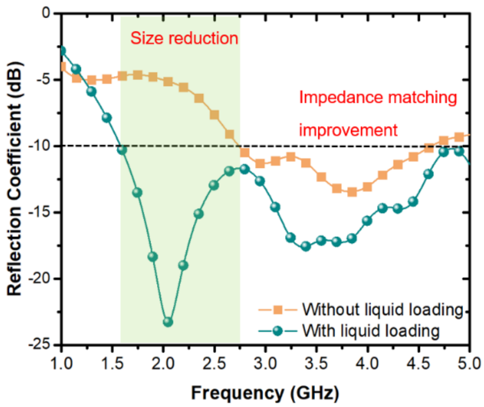

FIGURE 5. Simulated reflection coefficient of the proposed metal cone-shaped monopole antennas with and without using the liquid loading.

is changed to a hollow cone with a diameter of 49 mm and a height of 39.6 mm. The entire hollow cone is immersed into the liquid. Such a configuration is difficult to be realized by using the conventional solid dielectric materials (due to the fabrication complexity of accommodating the hollow cone), therefore, our proposed liquid materials could have unique advantages in this scenario. The simulated reflection coefficients of the proposed metal cone-shaped monopole antenna with/without using the liquid loading are depicted in Fig. 5. The original metal cone antenna covers a band of 2.75 – 5 GHz (FW = 58%). By loading it with the ionic liquid a much lower resonant frequency at 2 GHz and a wider bandwidth from 1.6 to 5 GHz (FW = 103%) is achieved.

Importantly, different from the single band case presented in the previous section; in this design example, the liquid loading can simultaneously reduce the electrical size (∼ 42% reduction) and improve the broadband impedance matching of the antenna (see Fig. 5). This significantly improves the performance of such a wideband antenna. To gain an insightful view of the improved impedance matching, the complex input impedance of the cone antenna is given in Fig. 6. It can be seen that the liquid loading shifts the antenna resonance down to 2 GHz and 4 GHz (see red circles in Fig. 6 (b)). These resonances are due to the hybrid DR and metal cone resonant mode. For the wideband travelling-wave mode of the cone antenna, the resistance (real part of the antenna input impedance) is increased from about 35 Ω (no liquid) to around 45 Ω (with liquid) in the frequency

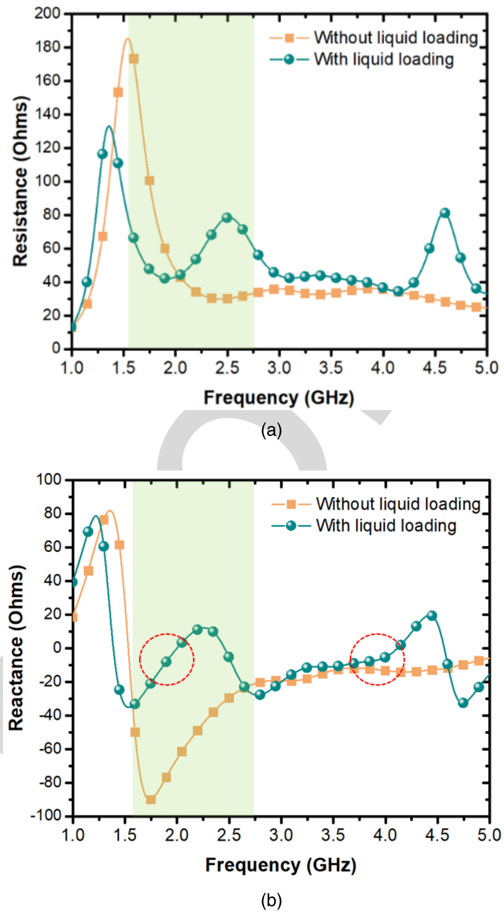

FIGURE 6. Simulated (a) real part (resistance) and (b) imaginary part (reactance) of the input impedance of the proposed metal cone-shaped monopole antennas with and without using the liquid loading.

band of 2.5 - 5 GHz. Such an improvement helps to reduce the antenna return loss by about 5 dB over the frequency band of interest.

III. WIDEBAND CP ANTENNA DESIGN

In the previous section, it has been demonstrated that the proposed ionic liquid loading can reduce the electrical size of the antenna by ∼ 40% and meanwhile improves the impedance matching of the wideband monopole antenna. Here, as a critical demonstration, we propose a broadband circularly polarized (CP) antenna which is typically very challenging to design. Again, we will further investigate the loading effect of the proposed ionic liquid.

A. RADIATION MODE CONVERSION

To convert the radiation mode of the antenna, a spiral slot is cut on the hollow cone, as shown in Fig. 7. The slot has three turns that are equally distributed from the bottom to the top of the cone. The detailed dimensions of the slot are provided in Fig. 7 as well. It should be noted that all antenna design examples in this paper have an identical overall dimension of 100 × 100 × 41 mm^3. In this case, the linearly polarized (LP) omnidirectional radiation of the original cone antenna could be transformed to CP boresight radiation

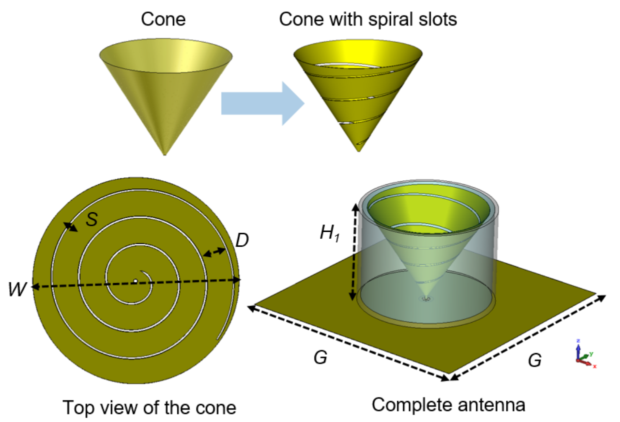

FIGURE 7. A spiral slot is cut on the metal cone-shaped monopole antenna. the complete antenna is loaded by using the proposed liquid. the dimensions are: H_1 (height of the container) = 40 mm, G (length and width of the ground plane) = 100 mm, W (diameter of the cone) = 49 mm, D (distance between the helix turns) = 6 mm, and S (size of the slot) = 0.66 mm. The overall dimension of the antenna is still 100 × 100 × 41 mm^3.

(cone antenna with spiral slots). The spiral cone antenna is also loaded with the proposed ionic liquid. Fig. 8 (a) depicts the simulated voltage standing wave ratios (VSWRs) of the spiral cone antennas with/without using the liquid. It can be seen that the proposed spiral cone antenna (no liquid) has a wide bandwidth and multiple resonances between 1.8 and 5 GHz. The resonant mode of the proposed antenna is quite similar to that of the helical antenna [27] where the main resonances are located at 2, 2.5, 3, 3.5 GHz and so on. However, the VSWR of a significant number of bands within these resonances are greater than 2. This is mainly due to the impedance mismatch between the antenna and the 50 Ω feed.

By loading the liquid, the lowest resonant frequency is decreased from 1.8 GHz to about 1.25 GHz while the VSWR over the entire band of interest is less than 2 (see Fig. 8 (a)). This shows that the electrical size of the antenna has been reduced by ((1 - 1.25/1.8)×100% = 30.6%) and the impedance matching over the wide band has been significantly improved. The effects on the VSWR of the liquid-loaded antenna at different temperatures are shown in Fig. 8 (b). The measured liquid data from −20 to 60 °C (as given in Fig. 1 (c)) is used to model the antenna. It can be seen that the proposed liquid antenna has stable performance over a wide range of temperatures, which is significantly better than that of the water/solvent-based solutions.

B. CIRCULAR POLARIZATION PERFORMANCE

The simulated electric field (E-field) distributions (at 1.57 GHz) of the proposed liquid-loaded spiral cone antenna are depicted in Fig. 9 at four different phase angles. It can be seen that the E-field is rotated clockwise from 0 °C to 360 °C with a constant phase delay (90 °C) and a symmetrical E-field variation. This verifies the right hand circularly polarized (RHCP) field generation of the proposed antenna. In addition, the frequency dependences of the simulated axial ratios (ARs) of the antennas with/without

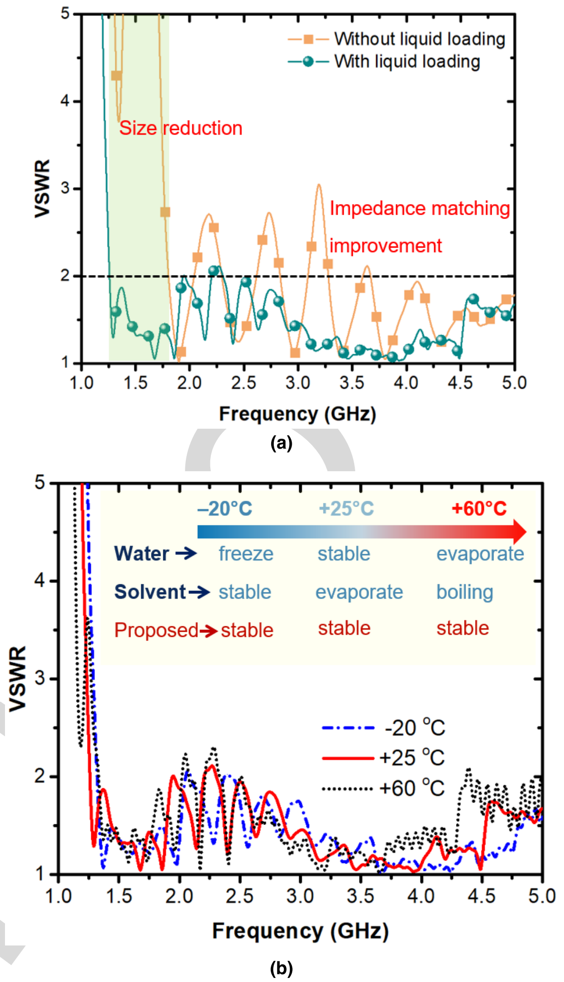

FIGURE 8. (a) Simulated VSWR of the proposed metal spiral cone monopole antennas with and without using the liquid loading. (b) Simulated VSWR of the proposed liquid-loaded antenna at different temperatures.

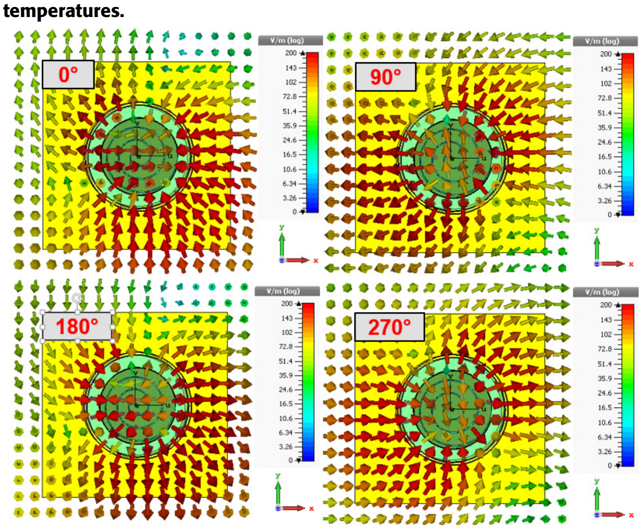

FIGURE 9. Simulated E-field distributions (at 1.57 GHz) of the proposed liquid-loaded spiral cone antenna at four different phase angles. The electric field rotates clockwise from 0 to 360 degrees.

using the liquid loading are shown in Fig. 10. The original antenna (no liquid) has a CP bandwidth (for AR < 3dB) at 2.15 – 2.7 GHz and 3.5 – 5 GHz whilst the liquid-loaded antenna has realized alternative CP bandwidths

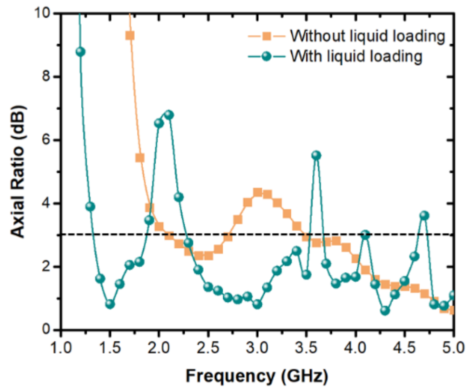

FIGURE 10. Simulated frequency dependences of axial ratios (ARs) of the proposed spiral cone antenna with/without using the liquid loading.

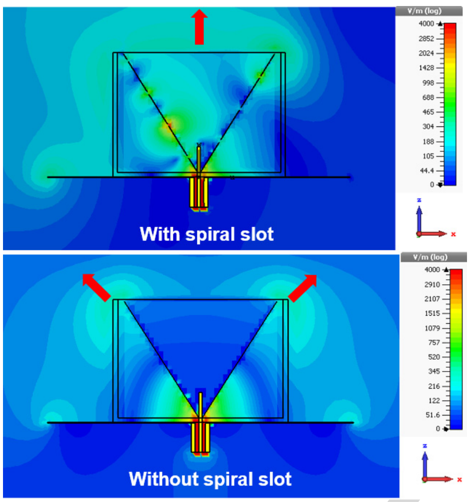

FIGURE 11. Simulated cross sections of the E-field at 1.57 GHz of the proposed liquid-loaded metal cone monopole antennas with/without using the spiral slots.

at 1.3 – 1.9 GHz, 2.25 – 3.5 GHz and 3.6 – 5 GHz respectively. These results show that the proposed liquid loading can improve the AR performance at lower frequencies and over a relatively wide frequency range.

It is worth noting that the radiation field of the spiral cone antenna is changed from omnidirectional (no spiral slots) to boresight radiation. As can be seen from Fig. 11, the liquid-loaded spiral cone antenna has a strong E-field distribution inside the hollow cone. The current travels via the spiral cone from the bottom to top. This enables the boresight radiation mode of the antenna. As can be seen from the red arrow marker, the liquid-loaded spiral cone antenna radiates the E-field to the boresight direction. In contrast, the E-field is mainly distributed outside the cone shape if the spiral slot is removed. Stronger E-fields can be observed at the bottom and the two edge comers of the cone. This shows that the cone antenna without loading the spiral slot has an omnidirectional radiation pattern with a radiation null at the antenna boresight direction.

IV. EXPERIMENTAL VALIDATIONS

A. ANTENNA PROTOTYPE FARICATION

To validate the antenna performance, we have fabricated the proposed liquid-loaded spiral cone antenna.

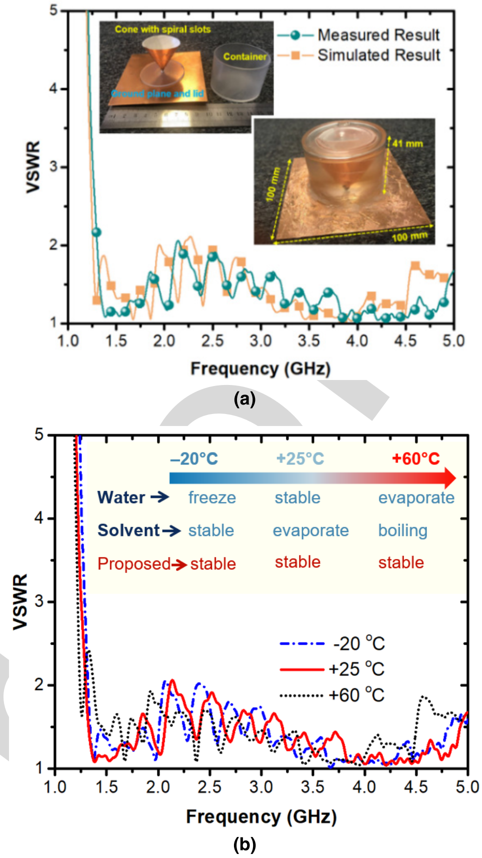

FIGURE 12. (a) Measured and simulated VSWR of the proposed liquid-loaded spiral cone monopole antennas. The picture of the fabricated antenna prototypes are shown as well. (b) Measured VSWR of the antenna prototype under different temperatures. The liquid antenna worked well in all cases.

The cylinder-shaped container and lid were machined entirely from a single rod of Perspex acrylic ($\varepsilon r \sim 2.5$). A copper sheet with a dimension of $100 \times 100 \times 0.1$ mm^3 was used as the ground plane. A probe-type SMA connector was placed at the center of the ground plane where the outer conductor was soldered to the copper sheet and the inner probe was configured through a hole on the sheet. The spiral cone was made using a copper thin film with a thickness of 0.01 mm. A hollow cone-shaped foam base was used to support the copper film. Once the container was filled by the proposed ionic liquid, the lid was pasted on the ground plane while the whole container was sealed using a Silicone rubber gel. The picture of the fabricated antenna prototype before and after filling the liquid is given in Fig. 12 (a).

B. ANTENNA PERFORMANCE MEASUREMENTS

The antenna was measured by using a Keysight portable VNA (N9917A FieldFox). The measured VSWR of the antenna prototype is given in Fig. 12 (a) along with the simulated results for comparison. Good agreement was obtained. The proposed antenna had a wide band from 1.25 to 5 GHz for VSWR < 2. The antenna prototype was also measured at different temperatures to show the excellent material stability of the proposed liquid loading material. As can be seen from

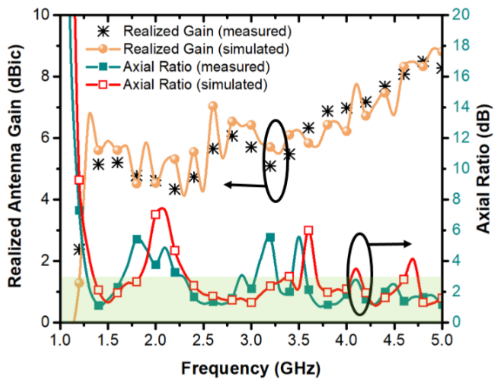

FIGURE 13. Measured and simulated frequency dependence axial ratios and realized gains for the proposed liquid-loaded spiral cone monopole antennas.

Fig. 12 (b), the measured VSWR of the liquid antenna was quite stable when the temperature varied from −20 to 60 °C. Other liquid materials, such as water and typical solvents cannot work well in such a wide temperature range. This is very important for real-world applications.

In addition, the measured and simulated ARs and realized gains of the antenna are given in Fig. 13. It can also be seen that the results were matched reasonably well. A wide CP bandwidth for AR $<$ 3 dB has been realized and the overall gain was higher than 4 dBic over the entire band from 1.25 to 5 GHz. The radiation efficiency was higher than 80% across the frequency band of interest. The measured and simulated RHCP and LHCP patterns at 1.57 GHz (GPS L1 band) are given in Fig. 14 over the E-plane (elevation plane) and H-plane (azimuth plane). It can be seen the proposed monopole antenna indeed has a boresight RHCP radiation pattern at this band with a half-power beam-width (HPBW) of 97.6 °C. The corresponding 3D radiation patterns for RHCP are shown in Fig. 14 as well. The antenna has realized a unidirectional boresight RHCP radiation field. These aforementioned results show that the proposed antenna could be used in GPS applications.

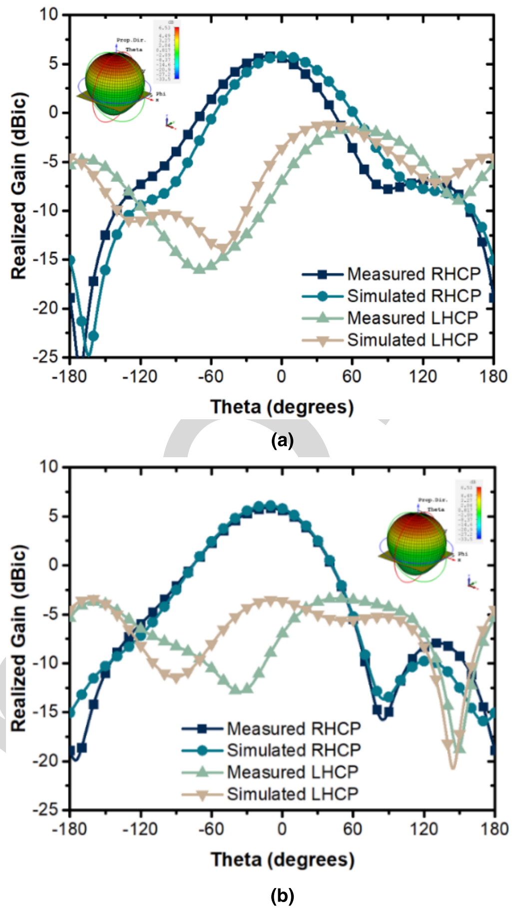

FIGURE 14. Measured and simulated RHCP and LHCP radiation patterns at 1.57 GHz of the proposed liquid-loaded spiral cone antenna. (a) E-plane patterns (b) H-plane patterns. The corresponding 3D patterns for RHCP are given as well.

V. DISCUSSIONS AND PERFORMANCE COMPARISON

To highlight the outstanding performance of the proposed liquid-loaded spiral cone antenna, some latest wideband monopole antenna designs are selected for performance comparison (see Table 1). It can be seen that our design has a relatively small electrical size compared with the existing work. In addition, the proposed design has achieved a relatively high gain and high efficiency over the frequency band of interest. More importantly, our proposed design has also realized a broadband CP radiation in the boresight direction, which is typically more challenging to achieve for such monopole-type antennas. All the above-mentioned features distinguish our work from the prior-art conventional monopole antenna designs. It is also shown that the proposed liquid loading scheme improves the antenna performance significantly. The proposed ionic liquid exhibits increased performance over more common liquid and solid materials and across a wide temperature range.

TABLE 1. Performance comparison with related work.

	[13] (2017) *IEEE TAP*	[18] (2019) *IEEE TAP*	This work (2019)
Frequency coverage (GHz)	0.58 – 2.99	0.69 – 3.35	1.25 – 5
Physical size (mm^3)	275 × 275 × 29	400 × 400 × 40	100 × 100 × 41
Electrical size (λ_0^3)	0.53× 0.53 × 0.06	0.92 × 0.92 × 0.09	0.42 × 0.42 × 0.17
Realized gain over the frequency band	6 – 8.5 dBi	4 – 6.5 dBi	4 – 8.5 dBi
Radiation efficiency	> 80%	> 80%	> 80%
Polarization	LP	LP	CP
Radiation mode	Omnidirectional	Omnidirectional	Boresight
Antenna type	Metal monopole	Solid dielectric-loaded monopole	liquid-loaded monopole

VI. CONCLUSION

A few monopole-type antennas loaded with an ionic liquid have been presented. The proposed liquid has significant advantages compared with water and other typical liquids in terms of temperature range, loss and material stability. To show the excellent performance of these liquid-loaded antennas, we have tested the antenna performance at different temperatures from −20 to 60 °C. It has been experimentally demonstrated that the liquid antenna performs well across a wide temperature range. The antenna had excellent performance in terms of size, bandwidth and efficiency. In addition, the liquid loading can reduce the electrical size of these antennas by 30-40% while improving the impedance matching over the wide band of interest. It is emphasized that the antenna designs presented in this paper are just examples to illustrate the advantages brought by the proposed liquid loading scheme. Other types of liquid-loaded wideband antennas can also be considered for different applications. We believe that this work will have a significant impact on developing compact and broadband antennas.

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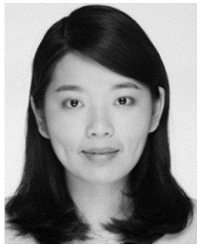

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